INVERSE ANALYSIS OF PLANE STRAIN AND UNIAXIAL COMPRESSION TESTS PERFORMED ON GLEEBLE

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Abstract

Plane strain and uniaxial compression tests are generally used for characterization of a material constitutive behavior during hot forming. Interpretation of the results obtained by such tests is complicated by flow inhomogeneity occurring in a specimen volume and temperature variations. Inverse analysis is an effective instrument allowing one to take these factors into account and obtain more accurate constitutive equations of a material. In this study the constitutive behavior of HC420LA steel was examined by plane strain and uniaxial compression testing on Gleeble 3800. Finite element simulation of the tests was performed in order to evaluate the flow inhomogeneity and its effect on stress-strain curves obtained as a result of testing. Inverse analysis was used to correct the initial Gleeble data and obtain accurate constitutive equations of the material.

Keywords: PSCT, uniaxial compression, plane strain compression, FEM, inverse analysis

1. INTRODUCTION

Specification of constitutive equations describing the material flow stress is necessary for design and optimization of technological procedures in forming [1]. Computer aided simulation of forming processes based on finite element method (FEM) is applying in optimization of energy consumptions of the production, preventing defects in the product, reducing the load on the equipment, increasing the utilization of a material and solving of other technological tasks [2-5]. The accuracy of constitutive models used in such simulations is critical.

Various tests are used in evaluation of material constitutive behavior. The type of a test should generally correspond to the stress strain mode realized in the simulated forming process. The plane strain compression tests (PSCT) and uniaxial compression tests (UCT) are usually applied for studies of processes such as rolling or forging that’s major stress-strain mode is compression.

The advantage of PSC test is that the area of contact between the specimen and the tools is almost constant during the test, thus the maximum effective strain value which could by accrued is relatively large. At the same time, significant flow inhomogeneity produced by rigid ands of the specimen are occurred which complicates the interpretation of the test results. The flow inhomogeneity occurring in UC test is much smaller but due to the increasing of contact area it is hard to obtain reliable data at large deformations when the effective strain is larger than 1.

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The flow inhomogeneity occurring in the specimens during the tests of both types complicates the interpretation of the tests results. Other factor having an influence of the stress-strain curves obtained by these tests is the temperature variation. Thus, the corrections of stress-strain data obtained from PSC or UC tests should be made to obtain real constitutive equations of the material. Different techniques were developed for correction of PSCT data [6-12]. The inverse analysis appears to be a most powerful of them providing the way of determination of constitutive equation constants [10-12] or evaluation of microstructure models [13]. The interpretation of the results of UC tests is in the focus of papers [14-16]. All these studies utilize inverse analysis to find the material constants and friction factor using FEM for solving the direct problem.

The objective of this work is the application of inverse analysis to characterization of HC420LA stainless steel constitutive behavior in a wide range of temperatures and strain rates using PSCT and UC tests performed on Gleeble 3800. The base idea of the characterization technique is follows. First the initial constants of constitutive equations are determined by approximation of Gleeble stress-strain data. These constants are then corrected by inverse method on a base on Nelder and Mead nonlinear simplex minimization of the error between the measured forces and the results of numerical simulation. The computer software was developed to realize this technique and applied to experimental data.

2. EXPERIMENT AND INITIAL APPROXIMATION

2.1. Experimental conditions

Plane strain and uniaxial compression tests were performed at high-strength automobile steel HC420LA on Gleeble 3800. Before the deformation the specimens were heated to the initial temperature 1100 °C when hold three minutes at this temperature and cooled to the temperature of deformation (980, 1030 and 1050 °C). The deformation was performed at strain rates 0.1, 1 and 10 s^{-1} to the nominal effective strain of 1.

The initial geometry of UC tests specimens was a cylinder of 15 mm height and 10 mm diameter. For the PSC tests the bricks of initial dimentions 10x15x20 mm were used, the tool width was 5 mm. Graphite lubricant and tantalum foils were used in order to eliminate friction between specimens and the tools. The temperature during hte test was measured by a thermocouple placed at the middle of lateral surface of a specimen.

2.2. Initial approximation

The approximation of constitutive behavior of steel in conditions of hot forming can be constructed as a set of equations taking into account strain hardening, dynamic recovery and dynamic recrystallization processes [17-19]:

$$\sigma = X_d\sigma_{drx} + (1 - X_d)\sigma_{drv}(1 - \exp(-\Omega\varepsilon))^m, \tag{3}$$

$$X_d = 1 - \exp\left(-k(\varepsilon - \varepsilon_c)\right)^n, \tag{4}$$

$$\varepsilon_c = A_e\left(\dot{\varepsilon}\exp\left(\frac{Q_e}{RT}\right)\right)^d, \tag{5}$$

$$\sigma_{drx} = \frac{1}{\alpha_{drx}}\operatorname{asinh}\left(A_{drx}\left(\dot{\varepsilon}\exp\left(\frac{Q_{drx}}{RT}\right)\right)^{m_x}\right), \tag{6}$$

$$\sigma_{drv} = \frac{1}{\alpha_{drv}}\operatorname{asinh}\left(A_{drv}\left(\dot{\varepsilon}\exp\left(\frac{Q_{drv}}{RT}\right)\right)^{m_v}\right). \tag{7}$$

where X_d is treated as a dynamically recrystallized fracture; ε_c – critical strain for initialization of dynamic recrystallization; $R(= 8.31)$ is the universal gas constant; Ω, m, k, n, A_e, Q_e, d, α_{drx}, α_{drv}, A_{drx}, A_{drv}, m_x, m_v, Q_{drx} and Q_{drv} are the constants to be determined.

The experimental stress-strain data were approximated by eq.(3)-(7) using least square method and Nelder-Mead minimization procedure. The results of approximation compared with Gleeble data are presented in

Fig. 1. It can be seen that the approximation constructed fits the experimental data within the given temperature and strain rate range.

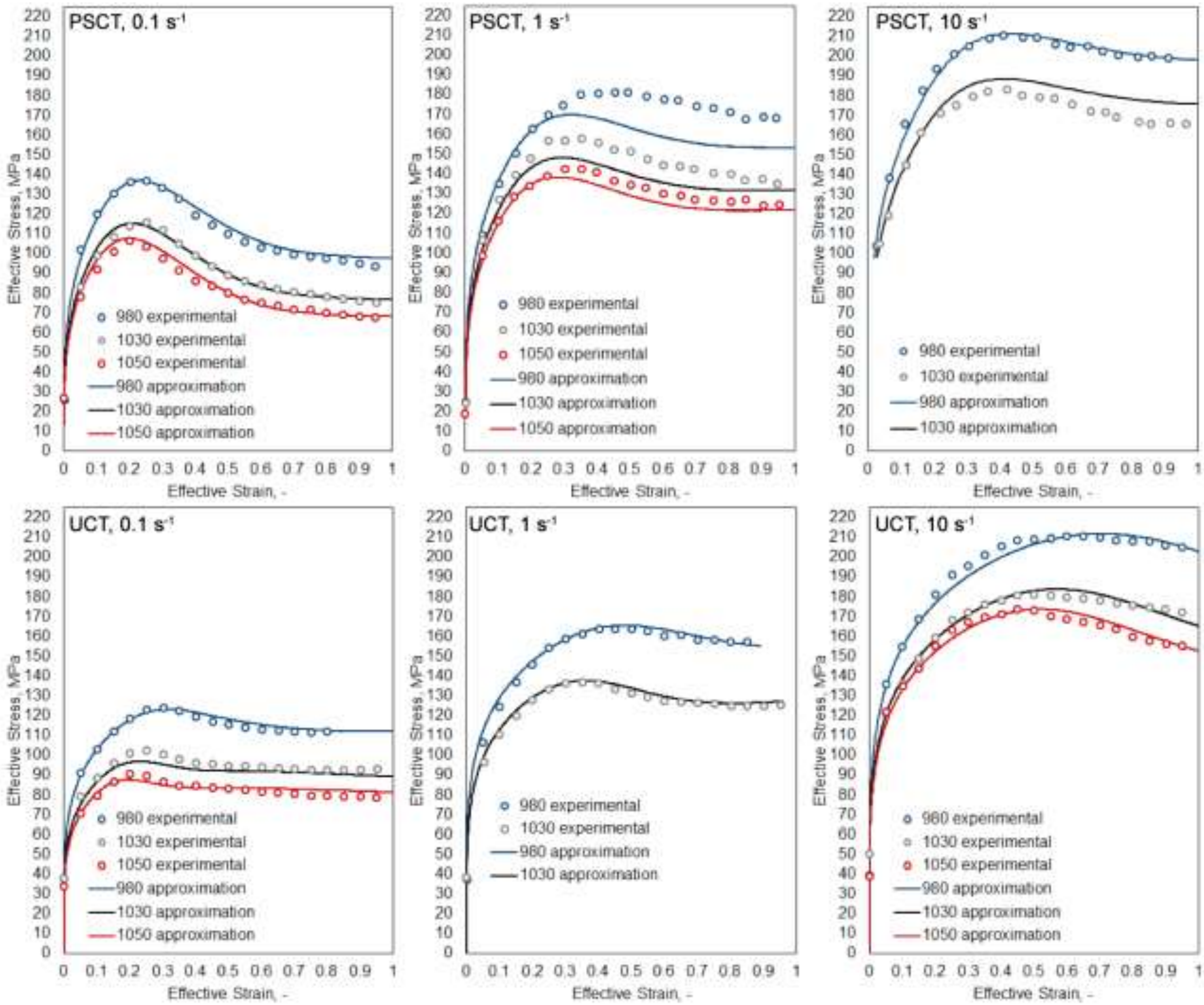

Fig. 1 The initial approximation of stress strain curves obtained by PSC and UC tests at different temperatures and strain rates

3. RESULTS AND DISCUSSION

3.1. Finite element analysis

Finite element analysis was performed in order to study flow inhomogeneity occurring in a specimen during the tests. The software realizing numerical simulation of the tests was developed by the authors on a basis of SPLEN [3] FE code. Axisymmetric FEM formulation was used to simulate the UC tests, for the simulation of the PSC tests, 2D plane FEM formulation with the corrections proposed in [11] was used to simulate PSC tests. The temperature of a specimen was considered to be distributed uniformly by its volume and varied in time according to the values recorded during the test. The distributions of the effective strain rate and the effective strain obtained by the simulations of PSC test at nominal strain rate 1 s^{-1} and UC test at nominal strain rate of 10 s^{-1} are illustrated in **Fig. 2**. The nominal temperature of both tests was 1050 °C.

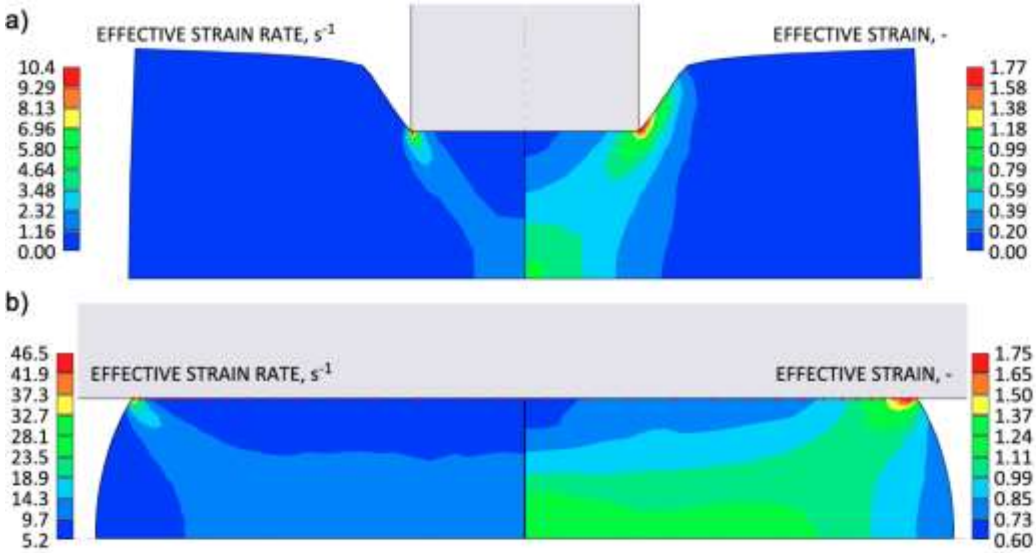

Fig. 2 The effective strain rate and the effective strain distributions obtained by finite element simulation of a) PSC and b) UC tests at the temperature of 1050 °C

The distributions illustrated on fig. 2 demonstrate that significant flow inhomogeneity occurs in a volume of the specimens during the tests of both types. The value of nominal strain for the PSC test presented on **Fig. 2a)** is 0.5, at the same time, local effective strain in the center of the specimen is 60% higher and reaches the value of 0.8. **Fig. 2b)** illustrates the results of simulation of UC test with nominal strain of 1, it can be seen that local effective strain reaches the value of 1.2 in the center of the specimen.

3.2. Correction of the constitutive models

As the constitutive equations constructed by the initial Gleeble data dos not take into account flow inhomogeneity taking the place in a specimen volume they need to be corrected. These equations are considered as an initial approximation which is used than as an initial guess for the inverse analysis based on FE simulation.

The aim of finite element simulation of the tests is to predict the evolution of force acting on tools as correctly as possible. Comparison between the measured forces and the predicted ones allows one to evaluate an adequacy of constitutive equations used in the simulations. The constitutive equation constants than should be iteratively corrected to minimize the deviations between measured values and the predicted ones. In this work the initial values of constitutive equation constants were corrected to minimize the objective function:

$$E = \sum_{i=1}^{N} \frac{1}{t_i} \int_0^{t_i} \left(F_m(t) - F(t)\right)^2 dt \qquad (8)$$

where N is the number of tests, t_i is the duration of i-th test, F_m is the measured load and F is the load predicted by FEM.

The comparison of the loads obtained by numerical simulation before and after correction of constitutive equations with the experimental data is presented in **Fig. 3**. It can be seen that before the correction of, the loads predicted by FEM are higher than experimental ones. After the correction the deviations between the predicted values and the experimental ones are much smaller. At the same time it can be noticed that UCT data needs smaller correction than PSCT ones. The loads predicted by initial PSCT data are significantly higher then experimental ones so the initial stress-strain curves obtained by PSCT may overestimate real effective stress values by 10-20%. The overestimation of effective stress values produced by UC tests is not so significant and reaches about 3-5%.

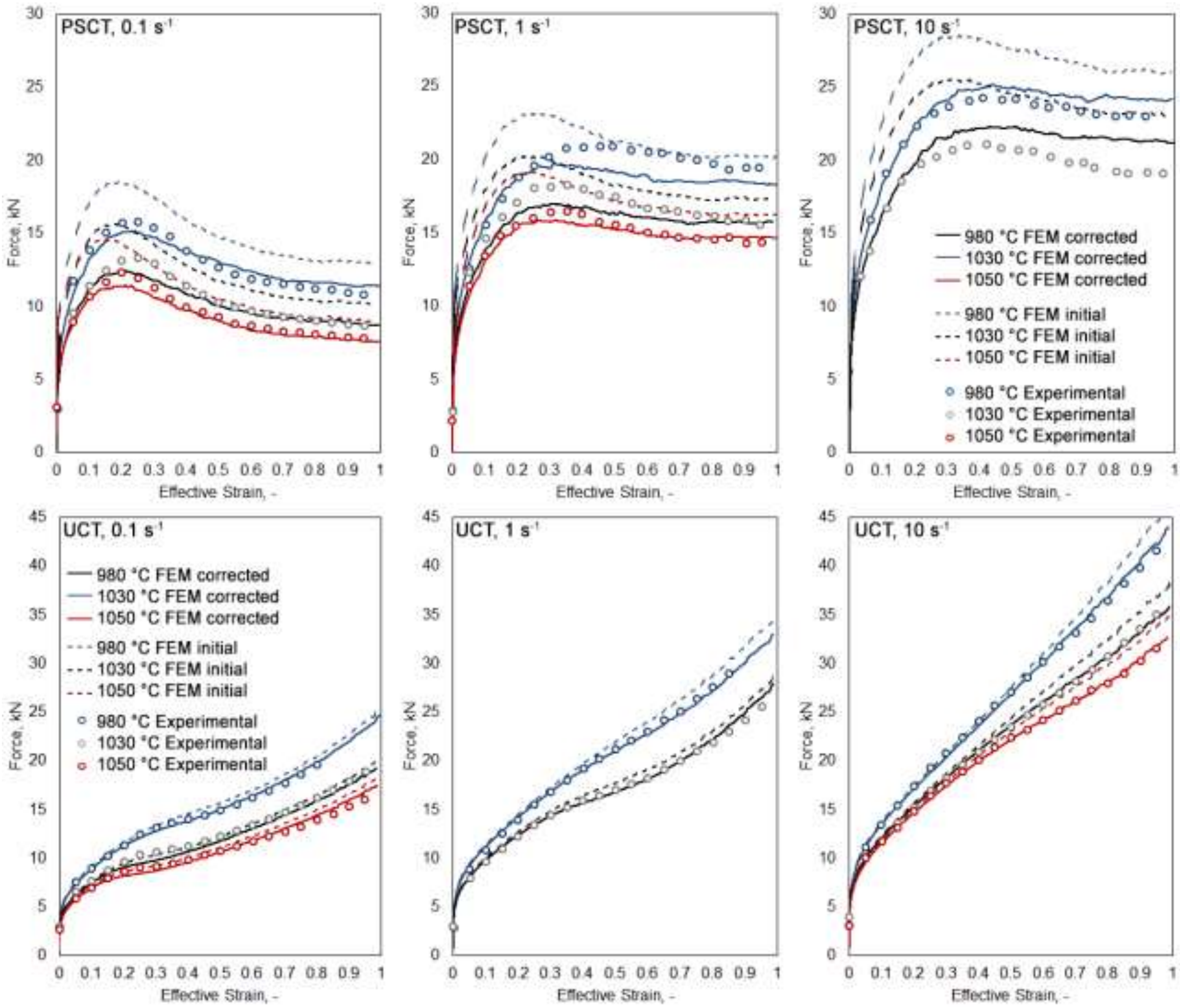

Fig. 3 The evolution of the force acting on the tool during the tests obtained by numerical simulation before and after the correction of constitutive equations compared with the experimental data

4. CONCLUSIONS

Large strain and strain rate inhomogeneity occur in specimen volume during PSC of UC tests. As a result, the real effective strain in the center of the specimen can be about 60% higher for the PSC tests and 20% for the UC ones.

Constitutive equations obtained by approximation of initial Gleeble data may overestimate the effective stress values. The stress-strain data obtained by PSC and US tests should be corrected using inverse analysis to produce reliable data for constitutive equations.

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